Implications of Wavelet Analysis to Reservoir Quality and Reserve Estimation: A Systematic Approach to Wavelet Estimation with an Example Case Study from the Deep Tuscaloosa Trend, Pointe Coupe Parish, Louisiana, USA

Michael L. Shoemaker, William A. Hill, and Philip N. Trumbly, BP America, Inc.*

Summary

When interpreting reflection seismic data, inaccuracies in estimating correct zero-phase wavelets can often be overlooked. Adverse consequences, such as unknown seismic polarity and phase, well miss-ties, and erroneous structural / stratigraphic interpretation, may not be realized when attempting to calibrate subsurface geology to seismic data. Wavelets can be particularly critical, for example, when prospecting for hydrocarbons at depths exceeding 20,000 feet, where drilling and completion costs can exceed 20 million US dollars per well. At such depths, 50 ft of structural error, or 1-2 seismic samples equivalent, can be the difference between a prolific or uneconomic well, emphasizing the importance of an accurate seismic interpretation. In hopes of minimizing the risk of both stratigraphic and structural interpretation, a systematic 12-step wavelet estimation methodology was developed and tested. This technique is applied to the onshore deep gas Tuscaloosa Trend, whereby fictitious phase shifted data integrated with model based inverted seismic impedance is used in quantifying the accuracy of the method**.** This example demonstrates that an incorrect wavelet can potentially result in an invalid seismic interpretation, and potentially adversely affect hydrocarbon reserve estimates.

Introduction

A wavelet, as defined in the convolution model, is a transient signal or filter of finite duration containing inherent sinusoidal waveform components characteristic of the seismic traces that are inversely modeled and interpreted. The sinusoidal components are intrinsically dependent upon filtering effects and passage of the source signal through the earth, and include information such as the amplitude, phase and frequency characteristic of the recorded seismic traces (Figure 1). It is obvious then, that an accurate well-based *deterministic-type* wavelet is essential to seismic interpretation, especially when interpreting subtle stratigraphic changes measured from well logs that are subsequently tied to seismic traces nearest the well bore.

An ideal wavelet, as defined by Sheriff (1995), is a short and sharp wavelet that bears a simple direct relationship to the reflective interfaces (of the earth), which reflections involve. A desirable wavelet is one that is zero-phase and is symmetric about time (t) = 0 (Figure 1). This results in maximum constructive interference or peak amplitude at t = 0 at stratigraphic boundaries we wish to interpret. A relatively "short" (usually < 100 ms), and compressed high frequency wavelet with minimal side lobes is usually preferred as to avoid interference (wavelet tuning effects) with closely spaced primary seismic events (e.g., tight sands); side lobe energy can constructively add with and blur closely spaced reflection events.

An incorrect modeled wavelet can eventually yield a seismic interpretation with minimal credibility resulting in: 1) unknown seismic phase and polarity convention, 2) poor seismic-to-well ties and seismic impedance-to-rock property ties, 3) an inaccurate structural / trap interpretation, and 4) an invalid seismic inversion solution. These factors can lead to prospects with minimal merit, and ultimately, unreliable reserve estimates. Some examples contributing to incorrect wavelets are poorly processed seismic data including, but not limited to, the incorrect application of pre and poststack deconvolution resulting in distorted wavelet phase, and an erroneous reflectivity series representative of poor well log measurements. Incorrect log measurements, for example, can be the result of formation damage caused by wash outs, and / or sonde cycle skipping, hydrocarbon (fluid) effects and dispersion.

In hopes of minimizing both stratigraphic and structural interpretation risk, a systematic approach to accurate deterministic-type wavelet estimation is proposed. The precision of the method has been quantified, via the full-bandwidth sparse spike acoustic impedance inversion technique (Pendrel and Van Riel, 1997), which bridges the gap between in situ (log) reservoir properties and reflection seismic data. 3D seismic data used in the study were acquired at a drained and abandoned prolific sandstone gas field of the Deep Tuscaloosa Gas Trend. Past cumulative gas production of the field, located in Pointe Coupe Parish, Louisiana, is estimated at over 75 BCFE.

Wavelet inaccuracies were quantified based on seismic phase and impedance differences from 3D inversion cubes. The inversion results were derived using identical job flows (see Saroka and Shoemaker, 2003) with the exception of two input variables, which were: 1) correct and incorrect wavelets, and 2) input seismic data with artificially induced differences in phase. The phase was deliberately distorted (or rotated) to illustrate the potential for erroneous interpretation caused by unknown wavelet polarity, a critical byproduct of poor wavelet estimation techniques. Final wavelet validity was determined by re-estimation of known gas reserves, dependent upon low seismic impedance connectivity (volumetrics) defined by log based rock property analyses.

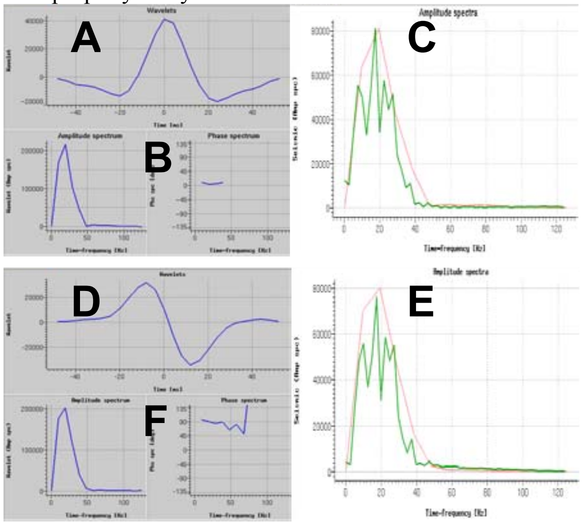

Figure 1. Symmetric zero-phase wavelet (A), amplitude and phase spectra (B), and input seismic amplitude spectrum (C, green) vs. modeled seismic (red). The bottom figure (panels D-F) shows sinusoidal components characteristic of the fictitious 90 degree phase shifted seismic data.

A Systematic Methodology for Wavelet Estimation

Fundamentally estimating a correct zero-phase wavelet involves an iterative deterministic process of shaping the earth's reflectivity (or reflection coefficients), representative of well impedance logs. Wavelet estimation is a process whereby an initial input signal, say a zero-phase Ricker wavelet of finite length and unaltered shape is first convolved with a well's sparse impedance log representing the earth's reflectivity series (minus attenuation effects, noise and multiples), and second, the wavelet is cross-correlated with seismic traces nearest the well bore in acquiring sinusoidal waveform components innate of the seismic data. These components are represented by amplitude and phase spectra, and modeled seismic (Figure 2, red traces) characteristic of the estimated wavelet.

This theory has been integrated into a comprehensive 12-step multi-iterative wavelet estimation methodology presented below (Table 1). The application of the method hopes to chronologically achieve: 1) definition of a seismic polarity convention commencement to interpretation, 2) identification of seismic stratigraphy via ties to well log properties and inversion, 3) delineation of regional structure for potential hydrocarbon trap and accumulation, and 4) accurate reservoir volumetrics and reserve estimates from structure and inverted impedance.

1. Identification of reservoir zone and corresponding seismic time gate where the wavelet is to be estimated from
2. Layer based observation and editing of any erroneous well log (compressional sonic and density) measurements as outliers via cross plot analysis
3. Pseudo log derivation (if necessary) of edited zones from step 2
4. Identification of wavelet peak energy relative to $t = 0$, and definition of seismic polarity
5. 1st pass wavelet estimation for initial tie, observed wavelet shape and symmetry, and recognition of any phase distortion (or rotation) from amplitude spectra
6. 1st pass well-to-seismic tie assessment via synthetic seismograms nearest the wellbore, and recognition of any discrepancies of time relative to well picks in depth
7. Bulk time shift of well for improved phase, and to align key seismic reflection events to sequence stratigraphic contrasts characteristic of the impedance well log, micro-shift impedance log as required for minimal synthetic residual vs. seismic
8. Identification of any multiples or invalid seismic events that do not tie to impedance log
9. Compare wavelet and seismic data spectra for similarities and contrasts, with particular attention to phase stability, and inspect for wavelet symmetry about $t = 0$
10. 2nd pass wavelet estimation and re-derive synthetics, inspect for improved phase and wavelet shape, and symmetry about $t = 0$
11. If wavelet is not zero-phase and symmetric about $t = 0$, repeat steps 7 through 10
12. Input final wavelet into inversion algorithm and validate inverted impedance results by means of rock property analysis; confirm that polarity convention (seismic response) conforms logically to rock physics (e.g., relative silica rich reservoir sand equates to a low impedance trough).

Table 1. An Iterative Methodology for Optimal Wavelet Estimation.

A Case Study from the Deep Tuscaloosa Gas Trend

The potential pitfalls in estimating an incorrect wavelet is presented, whereby two hypothetical scenarios have been created to illustrate erroneous structural and stratigraphic interpretation outcomes. Scenario one: the aforementioned wavelet estimation method was applied, resulting in the zero-phase wavelet (Figure 1, top panel) implemented in the "correct" structural and stratigraphic interpretation of the example 3D seismic data. The interpretation has been confirmed by core data, log correlation, and production data. The resultant well-to-seismic tie is shown in Figure 2 (top panel). The seismic data were then inverted, producing a 3D impedance cube. Quantitative rock property analysis confirms a linear relationship between inverted seismic impedance vs. reservoir porosity, gross sand, and to some extent, volume-of-shale. Scenario two: the seismic data was fictitiously phase rotated by 90 degrees (Figure 1, bottom panel), and reinterpreted to show the adverse consequences of interpreting seismic data of unknown polarity, a byproduct of "poor" wavelet estimation practices. The phase shifted data was then reinverted using an identical inversion job flow, but with a *non-deterministic* synthetic zero-phase Ricker wavelet as input. The results were then compared, and are discussed below.

The 3D poststack seismic represent data acquired from the prolific onshore Tuscaloosa deep gas trend of southeast Louisiana, characteristic of over-pressured gas sandstone reservoirs at depths approaching 20,000 ft (6096 m). The Tuscaloosa sandstones in the study area are Cenomanian in age, and were predominantly deposited in a deltaic environment. The Tuscaloosa section is the first major growth fault expansion outboard of the ancestral Cretaceous-age Edwards and Sligo carbonate reef trends, and reflect a major depositional episode of clastics into the GOM basin. The Tuscaloosa reservoir sandstones, termed X, Y and Z (Figure 2) are remarkably porous for their depth of burial. Optimal sandstones representing "sweet spots" can contain porosities of 25% to nearly 30% at depths approaching 20,000 ft. Rock property analyses indicate that porosities greater than 20% can be readily identified from the inverted poststack seismic impedance. It's at one of these "sweet spots" where the methodology was tested, which is characteristic of a now drained and abandoned gas field that has produced 75 BCFE.

The correct tie (Figure 2, top panel), is represented by seismic traces nearest one of the wells within the abandoned field. The polarity is defined such that a decrease in impedance (product of volumetric velocity and density) represents a trough. Sands are labeled X, Y and Z. Notice the collaboration of the impedance log (blue) at seismic band, the gamma ray (red), and the defined seismic polarity (or trough) relative to the seismically interpreted sands (colored horizons). The synthetics are characteristic of a good match. Figure 2 (bottom panel) shows the resultant tie of the 90 degree phase rotated seismic data. Upon review, the seismic data appear to have been bulk shifted up by at least one-half seismic cycle; incidentally, the horizons have not changed location in space or time for both panels. The yellow horizon now conforms to the Sand X maker and the blue to the Sand Y marker. An additional horizon would now have to be interpreted representative of Sand Z. It is clear that the bottom panel represents an erroneous interpretation, which has resulted from unknown seismic polarity, even though the synthetic tie (red traces) is good. Hypothetically, interpreting the wrong sand

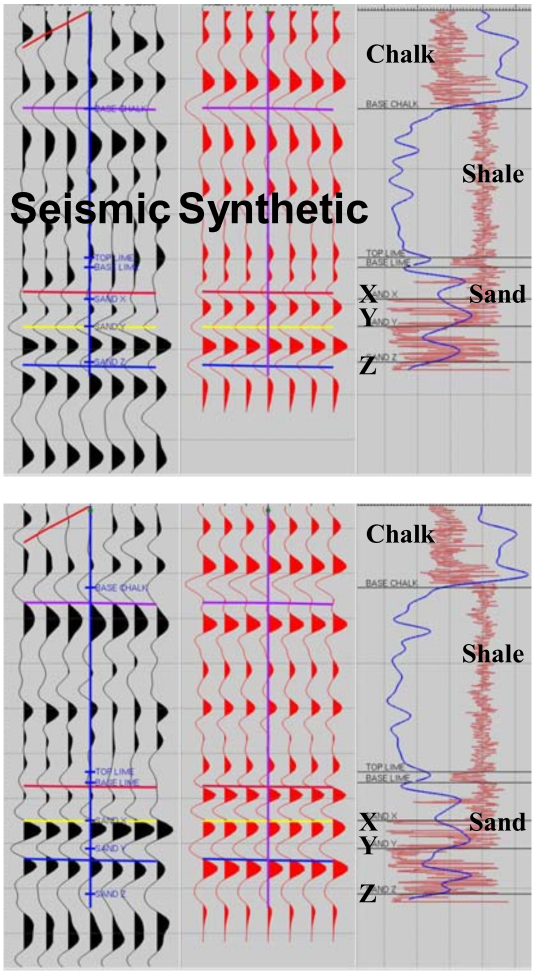

Figure 2. Well-to-seismic tie using the final estimated zero-phase wavelet (top panel), and tie using 90-degree phase shifted seismic, and arbitrary synthetic zero-phase Ricker wavelet (bottom). Filtered impedance log at seismic band, and gamma ray log are blue and red, respectively.

structurally in this case could have likely lead to negative economic drilling and development consequences, especially when, locally, 50 feet down dip can translate to the formation being wet. An incorrect tie can also result in an inaccurate reservoir trap definition. Here, the correct structural interpretation (Figure 3, top panel) results from correct well-to-seismic ties and known zero-phase seismic polarity; the horizon in the bottom panel represents the same interpreted Sand using the 90 deg. phase shifted data. It's apparent that the trap has changed from a 3-way orientation (top panel) to a 4-way, more optimistic, isolated style (bottom panel), potentially altering reservoir geometry, development strategies, and ultimately, reserve estimates.

Finally, inverted 3D impedance cubes, representing the abandoned gas field, were then compared relative to the effect of 90 deg. phase shifted seismic data (Figure 4, bottom panel) vs. the zero-phase data (Figure 4, top panel). The same Sand interval as in Figure 3 was used. Blue-to-red colors (or high and low impedance) represent more shaley and highly porous sand, respectively. Visual inspection of the bottom panel confirms a relatively more optimistic *stratigraphic* interpretation, suggesting better reservoir quality, or lower impedance. The phase shifted data suggests reservoir characteristics of less shale and better porosity, and potentially more reserves. In fact, volumetrics based on low impedance connectivity confirm an over estimation in reservoir volume by 3 billion ft^3.

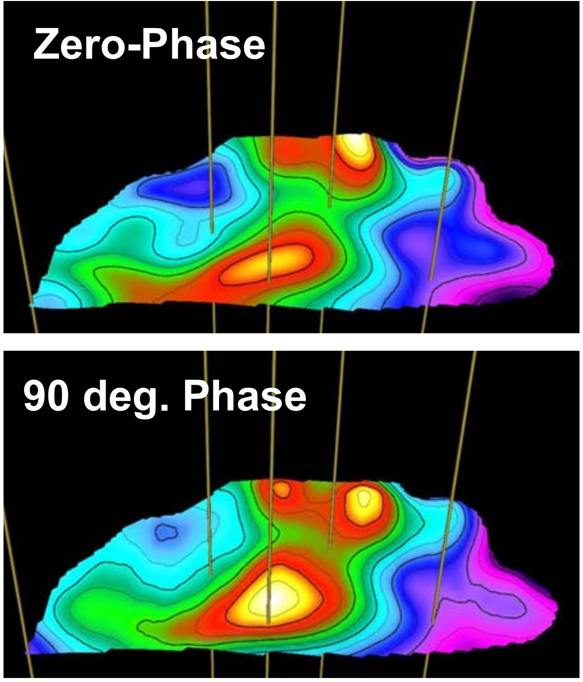

Figure 3. Structural trap orientation as a result of a correct tie using zero-phase data (top panel), and an incorrect tie using 90 deg. phase shifted data of same sand horizon.

Conclusions

A 12-step systematic approach to wavelet estimation has been proposed and the method confirms the necessary subtle detail required to effectively estimate a zero-phase wavelet prior to the onset of any seismic interpretation project. Consequences of poorly estimated wavelets include inaccurate structure / trap definition, unknown reservoir quality and geometry, and poorly estimated reserves, which in this case were overestimated by approximately 25%,for one sand layer. When appropriately risked, this input into the overall geologic mapping, reserve distribution analysis, and economic evaluation, can improve the high-grading of the prospect inventory.

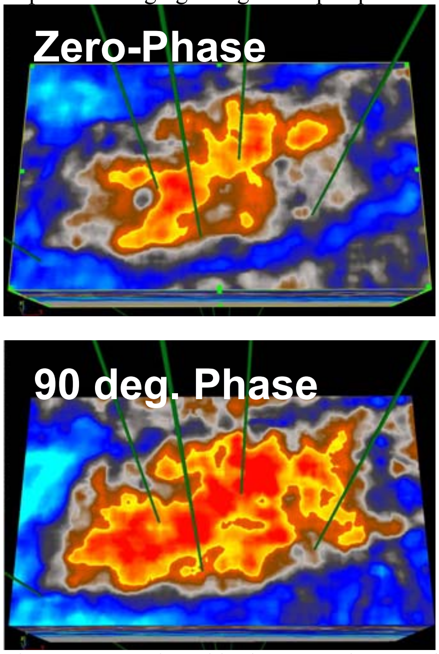

Figure 4. Stratigraphic interpretation resulting from 3D inverted seismic cubes (time sliced) using zero-phase seismic (top panel), and 90 degrees phase shifted seismic data (bottom panel).

References

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